Pentaquarks. Do they exist?

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1) Historical introduction: $SU(6)_{CS}$
2) Spectrum given by the chromo-magnetic interaction
3) Selection rules
4) Conclusions

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YES

Long time before the controversial T^+(1540) Y=2 states have been found in partial wave analysis in K^+p(d) scattering and put in the review of particle physics [1985 and 1992]

$$P_{11}(1720) \quad P_{13}(1780) \quad D_{03}(1865) \quad D_{15}(2074 \quad or \quad 2150)$$

Also a ? $^-$p resonance has been seen by NA49 at 1872 with a ? *(1520) p decay at the same mass.

These states may be interpreted within the constituent quark model as $qqqq\bar{q}$ states.

To build a pentaquark one should have as many constituents already present at the beginning of the reaction

The best:

$$K^+ n$$

$$(u\bar{s})(udd) \to uudd\bar{s}$$

The second possibility: deep inelastic on s d or $\bar{d}$ parton:

$$e^- + p(uuds\bar{s}) \to e^- + s\bar{d} + d(uud\bar{s})$$

$$e^- + p(uudd\bar{d}) \to e^- + \bar{d}s + \bar{s}(uudd)$$

$$\bar{n}_m + p(uudd\bar{d}) \to m^+ + \bar{u}s + \bar{s}(uudd)$$

$$n_m + p(uuds\bar{s}) \to m^- + c\bar{d} + d(uud\bar{s})$$

Third possibility: photo-production $g + p(uud) \to \bar{d}s + d\bar{s}(uud)$

Difficult: $e^- + p(uud) \to e^- + u(\bar{u}\bar{d}s) + (ud\bar{s})(ud)$

Still more difficult: $e^+ + e^- \to s(\bar{u}\bar{u}\bar{d}\bar{d}) + \bar{s}(uudd)$

Some skeptycism motivated by:

1) Why so low mass and a P-wave state?

2) Why so narrow?

3) m?$^{—}$ (1864) -m T^{+} (1540) = 314 > m_s - m_u

too large to be in the same multiplet

4) Where are all the states one one can build with 4q and a $\bar{q}$?

The study of SU(3) flavour exotic baryons is very old [H. Hogaasen and P. Sorba] and is inspired to the successfull derivation of mass splittings within SU(6) flavour-spin multiplets (De Rujula, Georgi and Glashow).

The chromo-magnetic interaction

$$\frac{\vec{s}\,\lambda_a(1)\cdot\vec{s}\,\lambda_a(2)}{r}$$

which gives contribution proportional to

$$C_6(d) - \frac{1}{2}C_3(d) - \frac{1}{3}C_2(d) - 4$$

for qq, while the opposit happens for $q\bar{q}$.

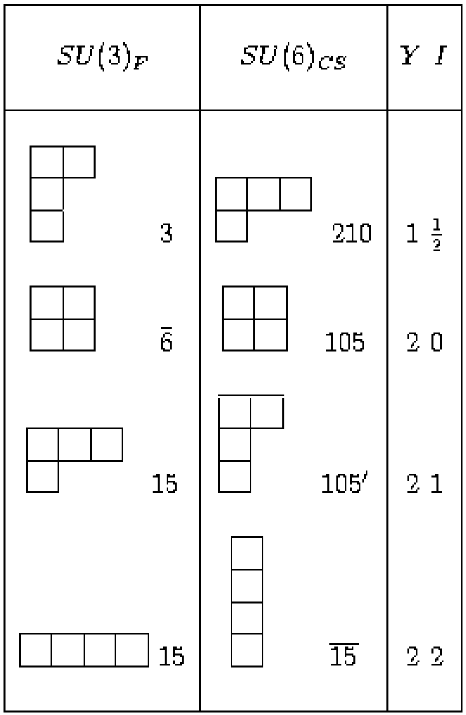
Let us consider a negative parity pentaquark with all the constituents in S-wave gives the mass formula

$$m^{-} = \sum_{i=1}^{4} m_{q_i} + m_{\bar{q}} - C_{qq}\left[C_6(t) - \frac{1}{3}C_2(t) - \frac{26}{3}\right]$$
$$+ C_{4q,\bar{q}}\left[C_6(p) - C_6(t) - \frac{1}{3}C_2(p) + \frac{1}{3}C_2(t) - \frac{4}{3}\right]$$

This implies that to get a low masses one has to look for high $SU(6)_{CS}$ Casimir representations for t and low Casimir for p

Fermion statistics relates the $SU(3)_F$ and $SU(6)_{CS}$ transformation properties to get antisymmetric wave function

$4q$ $\quad$ $4q\,\bar{s}$



Which shows that it is impossible to get 210_{CS} Y=2 states and that:

$$m(I=2) > m(I=1) > m(I=0)$$

which compares well with the D waves found

$$m(D15) = (2074\text{-}2150) > m(D03) = 1865$$

For positive parity states the presence of the orbital momentum changes the relationship between the flavour and the $SU(6)_{CS}$ transformation properties

We consider 4q in P-wave and the $\bar{q}$ in S-wave with respect to them. Moreover, since the chromo-magnetic interaction is at short-range one considers only the q pairs in S-wave for which one has

$SU(6)_{CS}$	$SU(3)_C \times SU(2)_S$	$\frac{\Delta m_{qq}}{C_{qq}}$
21	$(\bar{3},1)$	-2
21	$(6,3)$	$-\frac{1}{3}$
15	$(\bar{3},3)$	$+\frac{2}{3}$
15	$(6,1)$	$+1$

which gives lower mass to the states built with two 21's

Including the interaction with the $\bar{s}$, the spin-orbit term and the orbital kinetic energy gives the mass formula:

$$m(p) = \sum_{i=1}^{4} m_{q_i} + m_{\bar{q}} + \Delta m_{qq}^1 + \Delta m_{qq}^2$$
$$+ C_{4q,\bar{q}}\left[C_6(p) - C_6(t) - \frac{1}{3}C_2(p) + \frac{1}{3}C_2(t) - \frac{4}{3}\right]$$
$$+ a\,\vec{L}\cdot\vec{S}_q + K_1$$

If the two pairs are in P-wave [R.L. Jaffe and F.W. Wilczek], to $\bar{6}$ form a they combine into a 210 of $SU(6)_{CS}$ and

$$210 \quad x \quad \bar{6} \quad = \quad 1134 \quad + \quad 70 \quad + \quad 56$$

So we expect the lowest states to be a $J= 1/2^+$ I=0 one (as the T^+)

To get Y=2 I=1 states, which implies to start for 4 quarks from the product $6_F \ x \ \bar{3}_F = 15_F + 3_F$ we expect higher masses since one has to consider the $SU(6)_{CS}$ products $21 \ x \ \overline{15} \ = \ 210 \ + \ 105'$

And in fact the lower states predicted are the states (if one fixes the T^+ at 1540) P_{11} and P_{13}

$$m(P_{11}) = m(\Theta^+) + \frac{19}{32}(m_\Delta - m_N) = 1712$$

$$m(P_{13}) = m(\Theta^+) + \frac{19}{32}(m_\Delta - m_N) + \frac{3}{2}a = 1772$$

which compare well with the measured values 1720 and 1780 respectively

To every Y=2 state (I=0,1 or2) corresponds a I=3/2 ? particle and the one discovered at CERN may be a SU(3) partner of the P11(1706) state 1864-1712=152 !

The evaluation of the mass of the T+ has been performed by various authors

D. Diakonov, V.Petrov and M.V. Poliakov (1997)

H. Welgel (1998)

B. K. Jennings and K. Maltman (2004)

R. Bijker, M.M. Giannini and E. Santopinto (2004)

C.E. Carlson, C.D. Carone, H.J Kwee and V. Nazaryan (2003)

J.J. Dudek and F.E. Close (2004)

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F. Stancu and D.D. Riska have shown selection rules for pentaquark decays

Jaffe when studying the $qq\overline{q}\overline{q}$ mesons, discovered that these states may decay just by the separation of the constituents and named the corrisponding decay channels “open doors”. This property follows from the transformation properties of the pseudoscalar particles M to be $SU(6)_{CS}$ singlets. Therefore for only the $qq\overline{q}\overline{q}$ states, which are $SU(6)_{CS}$ singlets the MM final state is an “open door” channel. Since the CMI gives large negative contributions to $SU(6)_{CS}$ colour singlets, the very broad width $f^0(600)$ I=0 0^+ state may be interpreted as a $qq\overline{q}\overline{q}$ state.

One expects the $J^P = 1/2^-$ state to have too broad widths to be disentagled from the background. Instead one expects to identify the D-wave states and in fact we predict for the lowest D I=0 and I=1 states to be D_{15} and D_{03} and the mass difference

$$\frac{3}{4}\left(m_\Delta - m_N\right) = 218$$

which compares well with the range (2074-2150) –1865 = (209-285)

Similar considerations can be made for baryons. In fact the states of $SU(6)_{FS}$ the 8 1/2+ and 10 $3/2^+$ transform as a 70 and 20 of $SU(6)_{CS}$, which implies “open doors” channels for the decay of a pentaquark into them and a pseudoscalar meson only if they transform as the same $SU(6)_{CS}$ representation

70 to decay into $1/2^+$ 0^-
20 to decay into $3/2^+$ 0^-

Since these states and also the lighter ones.

Some considerations on $qq\bar{q}\bar{q}$ mesons

Some year ago L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer identified the (f^0 + A^0)(980) mesons as hidden strangness $(qs)(\bar{q}\bar{s})$ states supported by KLOE evidence in favour of this content.

Since the mass of the these states is about $2\ m_K$, we expect, on symmetri reasons, that the lowest I=0 0^+ state should be around the $2\ m_p$ threshold and so may not be identified with the f^0(600) state, which should be identified (almost) with the $SU(6)_{CS}$ singlet built with a $15\ x\ \overline{15}$ of $SU(6)_{CS}$ (the lightest with a $21\ x\ \overline{21}$)

By fixing the coefficients of the combinations of Casimir to the mass of the f^0(600) and (f^0+A^0)(980) states one can derive the mass of the other mesons

For positive parity states, we expect only few states to have a detectable signal in the baryon-meson channel, into the 8 $1/2^+$ 0^+ the states which transform as a 70 $S=1/2^+$ of $SU(6)_{CS}$

Below 1800MeV we have only the

$$\Theta^+_{\frac{1}{2}}(1540) \quad \Theta^+_{\frac{3}{2}}(1590) \quad P_{11}(1706) \quad P_{13}(1767)$$

Conclusions

1) The CM interaction predicts the existence of a $\overline{10}$ 1/2$^+$ as the lightest pentaquark

2) By relating the mass splittings within the pentaquarks to the baryon (? -N) and fixingthe kinetic energy one predicts

$$m(P_{11})(1720) - m(\Theta^+) \cong 178$$

and also the right sign and order of magnitude for $m(D_{15}) - m(D_{03})$

3) The SU(6)$_{CS}$ selection rule, which implies that only the states transforming as a 70 (20) may decay into a baryon (decuplet) plus a meson accounts for not finding the S-wave at about the same mass of the T$^+$ and accounts for the few P-wave states found

4) Look for phse-shift angles of K$^+$p and K$^+$n or deep inelastic processes where a s (or $\bar{d}$) is removed from the proton, so that the valence quark and the remaining $\bar{s}uud$ (or $uudd$) need simply a d (or an $\bar{s}$) to build a pentaquark